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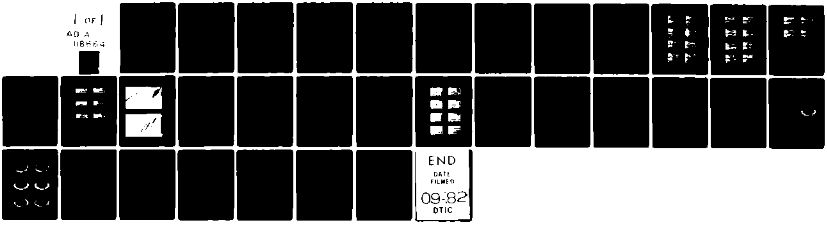

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research accomplished with first year support by AFOSR Contract No. 80-0051, "Intense Relativistic Electron Beam Investigation", was reported in the "Interim Scientific Report to the AFOSR for the period October 1, 1979 to September 30, 1980" and is herewith included by reference as part of this final report. Progress during the second (final) year of this contract is reported herein. In particular the following topics are discussed: a. collective ion acceleration experiments using relativistic electron beams and localized ion sources produced by thin films, filaments, puffed gases and vaporization of small diameter wires; and b. electron

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AFOSR-TR- 82-0657

Final Scientific Report to the

Air Force Office of Scientific Research

from the

Department of Physics
School of Physical and Mathematical Sciences
North Carolina State University at Raleigh
Raleigh, North Carolina 27650

for the period October 1, 1979 to September 30, 1981

INTENSE RELATIVISTIC ELECTRON BEAM INVESTIGATIONS

AFOSR Contract No. 80-0051

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TABLE OF CONTENTS

I. ABSTRACT

Research accomplished with first year support by AFOSR Contract No. 80-0051, "Intense Relativistic Electron Beam Investigations," was reported in the "Interim Scientific Report to the AFOSR for the period October 1, 1979 to September 30, 1980" and is herewith included by reference as part of this final report. Progress during the second (final) year of this contract is reported herein. In particular the following topics are discussed: (a) collective ion acceleration experiments using relativistic electron beams and localized ion sources produced by thin films, filaments, puffed gases and vaporization of small diameter wires; and (b) electron beam quality studies experiments in collaboration with Drs. Robert K. Parker and V. L. Granatstein at the Naval Research Laboratory with the objective of obtaining "cool" beams propagating in vacuum in an axial magnetic field with minimum energy spread for such applications as the free electron laser.

II. ACCOMPLISHMENTS

Three major areas of investigation were undertaken: intense electron beam transport in evacuated dielectric tubes; collective ion acceleration by intense relativistic electron beams; and electron beam quality studies and experiments related to free electron lasers. A complete list of all publications, abstracts, and theses prepared with support under this contract is given in Section III and copies of each of these are attached. The first of these experimental investigations was reported in the 1980 Ph.D. dissertation "Intense Relativistic Electron Beam Propagation in Evacuated Dielectric Guides," by Dean E. Pershing, copies of which were previously forwarded to AFOSR, and one copy of which is attached to this final report. A summary of accomplishments in the other two areas follows.

A. Collective Ion Acceleration Experiments Using Thin Films and Filaments

The initial ion acceleration experiments utilized thin films or nylon filaments stretched across the opening in the anode of an evacuated diode-drift tube section into which a relativistic electron beam was injected. The beam ionized the filaments and accelerated the ions in the direction of the electron beam by an axial electric field at the beam front. Ion energies up to 12 times the electron beam energy were observed. The detailed results of these investigations were reported in the 1981 Ph.D. dissertation, "Observations of Collective Ion Acceleration," by David Lee Morrow, copies of which have been forwarded to AFOSR and a copy of which is attached to this final report. The abstract of this work follows.

Linear collective acceleration of protons by a relativistic electron beam (0.5 MeV, 50 kA, 60 ns) was explored in the vacuum diode and vacuum drift tube. Nylon meshes, polyethylene films,

and nylon filaments as proton sources were tested along with the variation of cathode-anode-target spacings. Target activation was used to compare the various arrangements and to yield information concerning proton energies, amounts, and spatial distributions. Proton energies in excess of 7 MeV (12 times the electron energy) were produced with filaments in 30 cm long drift tubes. A few times 10^{10} particles were accelerated at this level. Activation was localized to a target spot and an axial streak on the drift tube wall. Electron beam behavior in the drift tube was examined with a Rogowski coil to measure the current and PIN diodes to measure Bremsstrahlung. In addition, the periodic activation of dielectric cathodes by radially accelerated protons is reported.

B. Collective Ion Experiments Using Puffed Gases and Vaporized Metal Wires

In addition to the above discussed experiments utilizing thin nylon filaments and films we have used other ion sources consisting of puffed gases and thin wires vaporized by external capacitors. This work is summarized below and will be fully documented in the 1982 Ph.D. dissertation by John R. Smith which is about 70 percent written at this time. Copies will be forwarded to AFOSR when they are available later this fall.

1. Introduction. Experimental results of the collective acceleration of ions from (1) a localized gas distribution and (2) a localized plasma are reported. A relativistic electron beam (0.6 MeV, 30 kA, 60 ns) is injected into an evacuated drift region through a 20 mm diameter anode aperture (Fig. 1). Near the anode end of the drift region an ion source is provided. At the drift tube end various ion diagnostics are attached to analyze the collectively accelerated ions. Also electron beam propagation which accompanies ion acceleration is examined via the Bremsstrahlung radiation process.

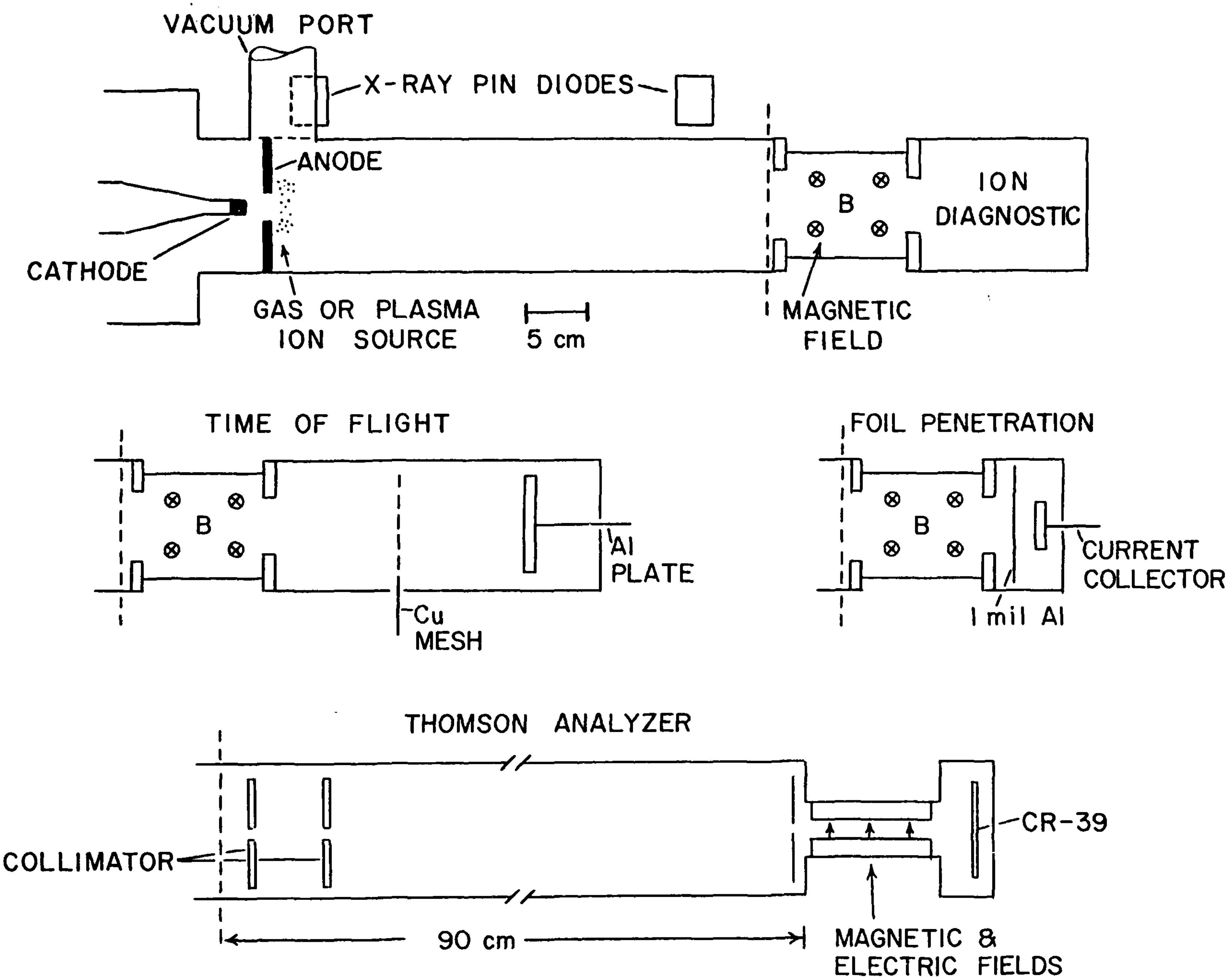

Figure 1.
Experimental configuration for collective acceleration with a gaseous or plasma ion source. Also shown are three ion diagnostic attachments: ion time of flight measurement, foil penetration ion current measurement, and Thomson parabola measurement.

In the first phase of this experiment a fast pulsed gas valve is used to create a localized gas distribution in the drift region at the time of beam injection. Ions are formed by interaction of beam electrons and gas. Three different gas types were used as the ion source (H, He, N).

For the second phase a preionized source is obtained by vaporization of small diameter wires. A capacitor energy storage system is discharged through two 3 mil tungsten wires or two 10 mil aluminum wires to produce the plasma. The wires are located just outside the beam channel in the vicinity of the anode. The e-beam and ion plasma source were timed to ensure that plasma is present during beam injection.

2. Ion Acceleration Measurements. Three measurements employed to analyze the ions are: (a) ion time of flight; (b) high energy component ion current measurement; and (c) Thomson parabola ion analyzer.

a. Time of Flight Measurements. The ion time of flight measurement consists of a copper screen wire mesh (60% transparent) and a flat disk aluminum collector separated by an axial distance of 10 cm. A 1.5 kG permanent magnet (l=75 mm) deflects beam electrons out of the channel. Typical time of flight traces are in Figs. 2, 3, and 4. Table 1 summarizes the results for the gaseous ion source shots. Note that part of the data was taken using a 9.5 inch I.D. drift tube rather than the usual 4 inch I.D. tube. It is seen that H ion shots have the greatest speed (1.2-1.8 cm/ns) whereas the heavier ion shots have slower velocities (0.5-0.7 cm/ns for N).

Table 1 Ion Time of Flight Velocity Measurements

Ion Source	Ion Velocity as Measured Using: Leading Edge (cm/ns)	Peak (cm/ns)
H	1.8 ± 0.5	1.5 ± 0.3
H*	1.3 ± 0.4	1.2 ± 0.4
He*	1.1 ± 0.2	0.8 ± 0.2
N*	0.7 ± 0.2	0.5

* 9.5 inch I.D. drift tube

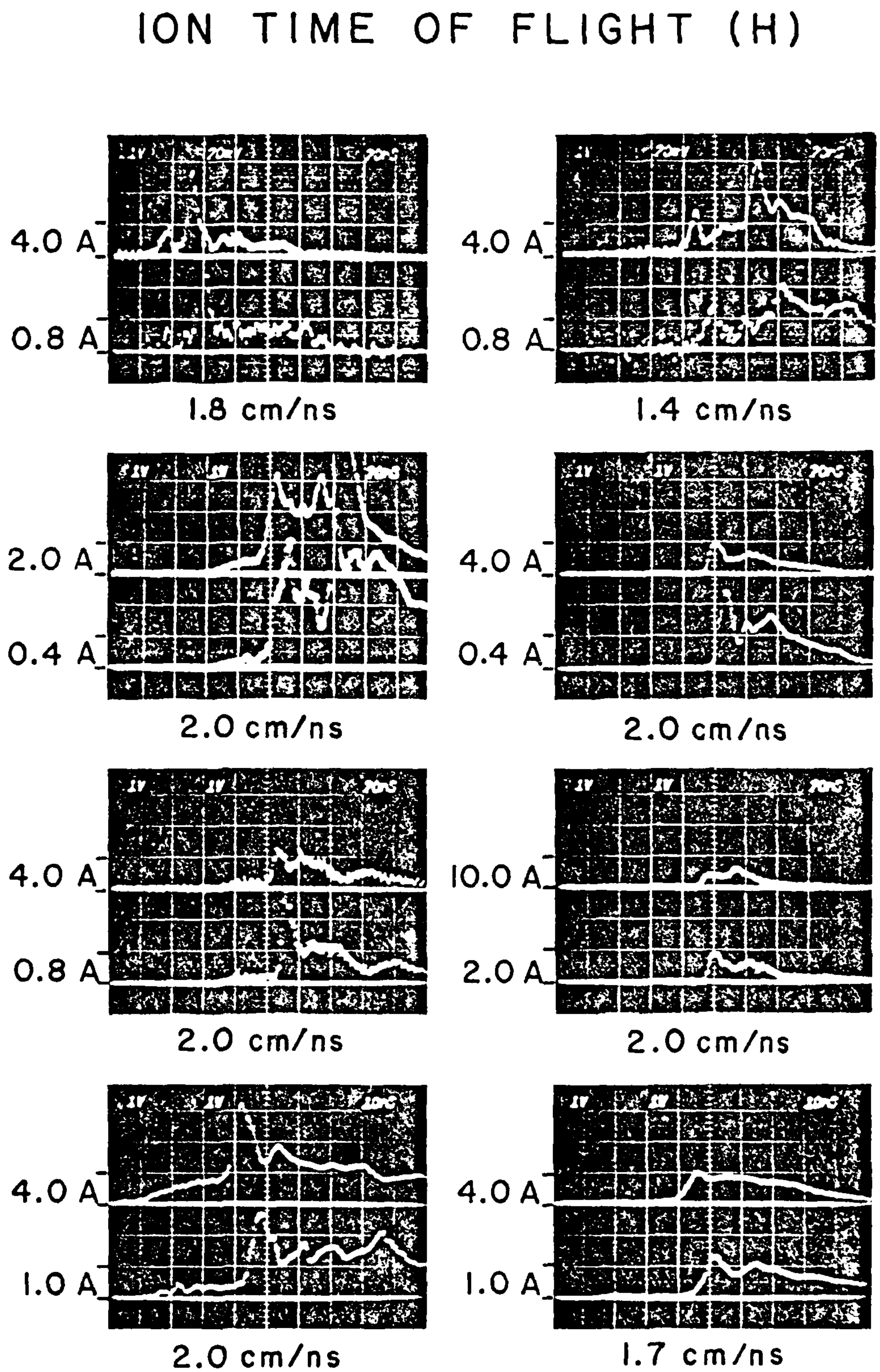

Figure 2.
Results for ion time of flight using H ion source. The upper/lower trace is the signal from the Cu mesh/Al plate. The average ion velocity over many shots is 1.8 cm/ns (4 inch I.D. drift tube) and 1.3 cm/ns (9.5 inch I.D. drift tube) where the pulse leading edge is used for measurements.

ION TIME OF FLIGHT (He)

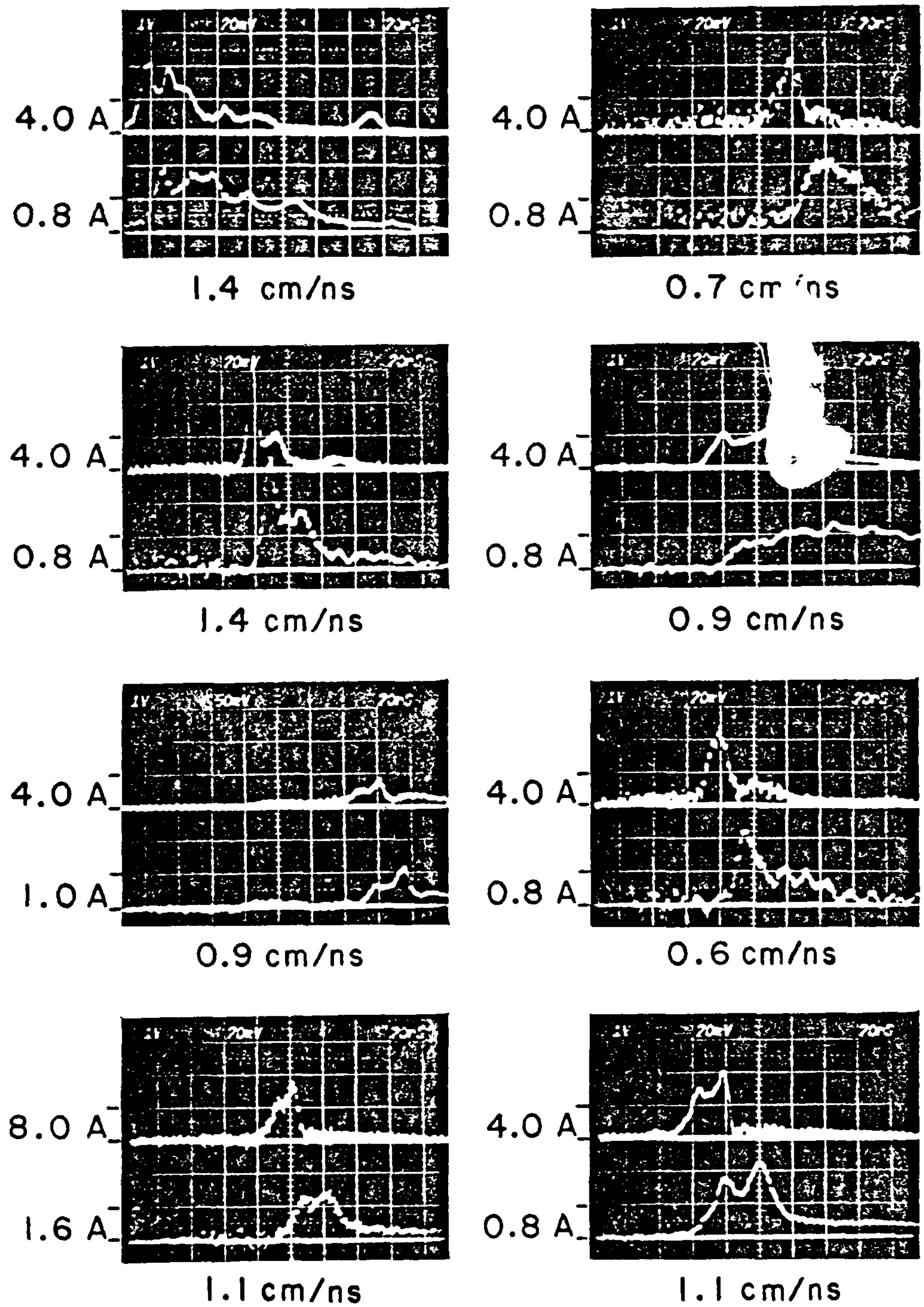

Figure 3.
Results for ion time of flight using He gas ion source. The upper/lower trace is the signal from the Cu mesh/Al plate. The average ion velocity over several shots is 1.1 cm/ns (9.5 inch I.D. drift tube) where the pulse leading edge is used for measurements.

ION TIME OF FLIGHT (N)

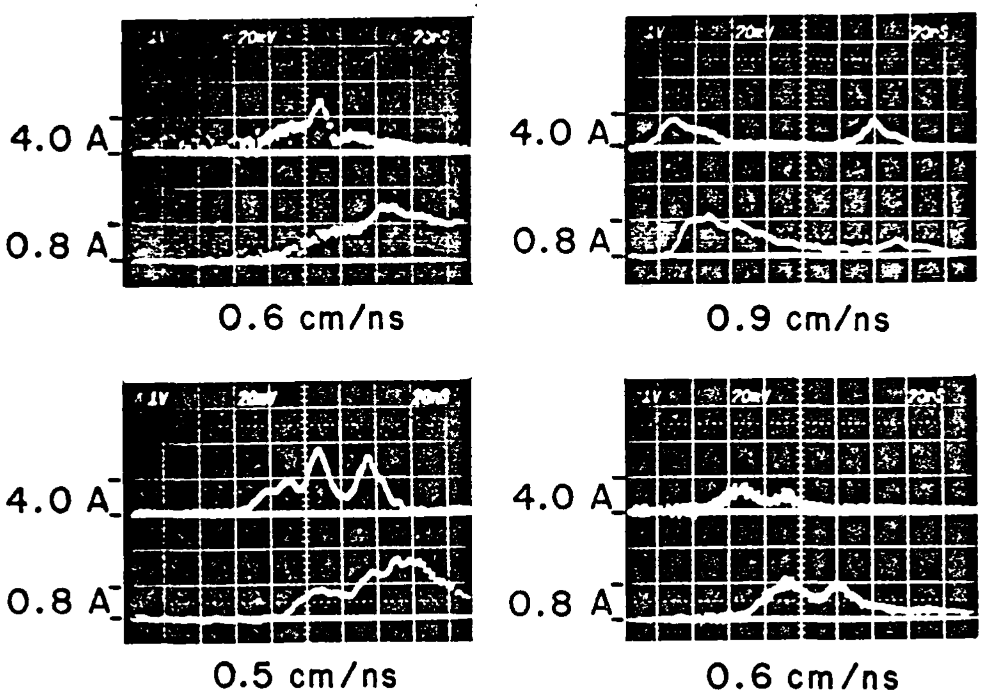

Figure 4.
Results for ion time of flight using N gas ion source. The upper/lower trace is the signal from the Cu mesh/Al plate. The average velocity over several shots is 0.7 cm/ns (9.5 inch I.D. drift tube) where the pulse leading edge is used for measurements.

b. Foil Penetration Measurements. An observation of the high energy component of the ion energy spectrum was made by measurement of the ions transmitted through a thin foil. For this diagnostic an ion Faraday cup is placed behind a 1 mil aluminum foil. Again, a magnetic field disposes of the beam electrons. Resultant ion current traces for the hydrogen gas ion source are shown in Fig. 5. Neglecting secondary electron currents and assuming the ions are protons, these measurements indicate 10^{10} to 10^{11} ions whose energy is greater than 1.5 MeV.

c. Thomson Parabola Measurements. The Thomson parabola ion analyzer represents the most definitive identification of ions. This diagnostic uses parallel magnetic (1.5 kG) and electric (5kV/cm) fields, which deflect ions into distinct parabolas according to their M/Z ratio. Ion tracks are recorded on a CR-39 plastic particle detector. The parabola fields have been independently calibrated to also permit an absolute determination of ion velocity. Using the ion mass as inferred from the M/Z parabola and the ion velocity as determined from the absolute calibration, the ion energy is calculated. Note in Fig. 1, the parabola analyzer is placed far downstream from where the beam is "dumped" to prevent plasmas from diffusing across field lines and exposing the CR-39 particle detector. Parabola particle tracks from two shots are in Fig. 6. Table 2 gives Thomson parabola results for both gas and plasma ion source shots. The first two columns give the gas or wire used and the shot identification number. The maximum velocities are shown (in cm/ns) for the ion species identified in each shot. Figs. 7 and 8 represent an analysis of the table in terms of maximum ion velocity and maximum ion energy versus ion mass. Major observations from the Thomson parabola data are: (1) maximum ion velocity is independent of ion charge state; (2) lighter mass ions achieve the greatest velocities; (3) maximum ion energy is not strongly

ION CURRENT MEASURMENT

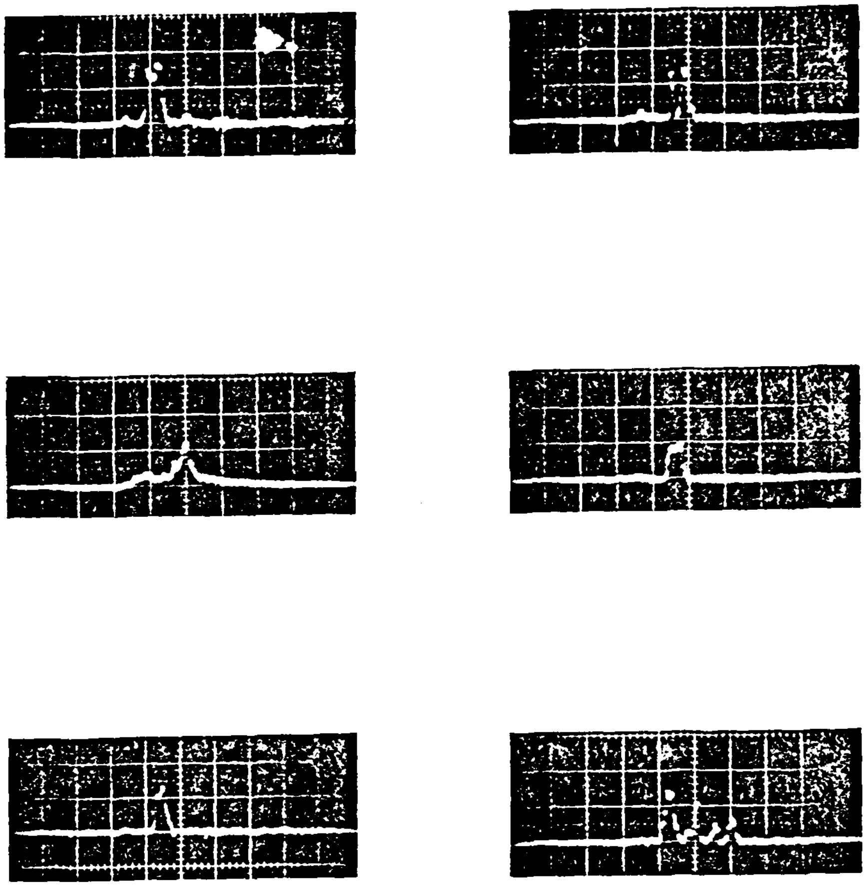

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Figure 5.
Results for the foil penetration ion current measurement. Neglecting secondary electron currents this measurement indicates approximately 10^{11} protons with an energy greater than 1.5 MeV.

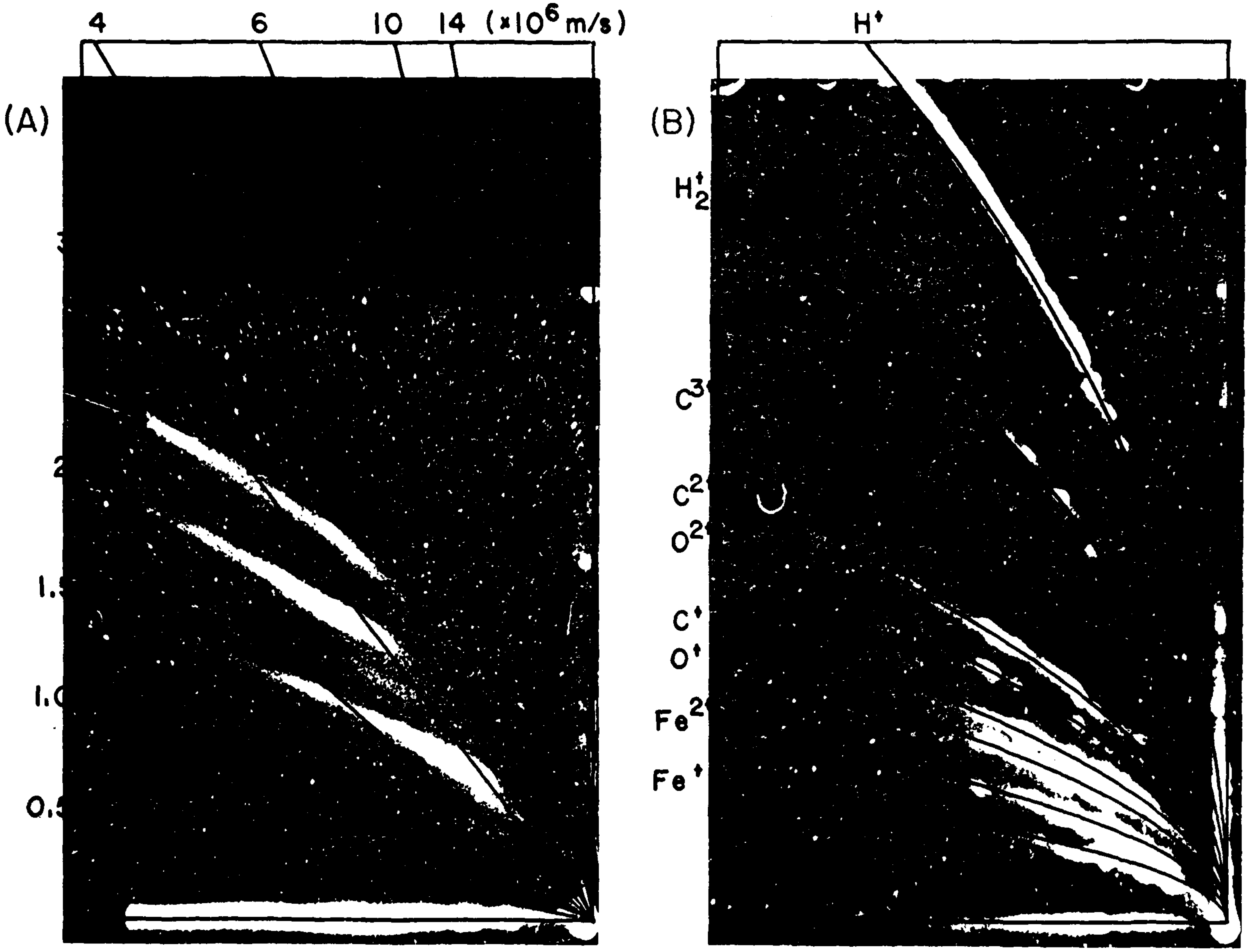

Figure 6.
Thomson parabola ion tracks for (A) He gas ion source - shot #100502 and (B) Al plasma ion source - shot #112303. Ions from these shots along with their maximum velocities are identified in Table 2. The overlay for (A) shows constant velocity rays ranging from (0.5-14) x 10^6 m/s. The upper trace is He^+. The lower traces are C^{++} and C^+ and each starts at 3.3 x 10^6 m/s. The overlay for (B) shows contours for various M/Z ratios ranging from 1 for H^+ to 56 for Fe^+.

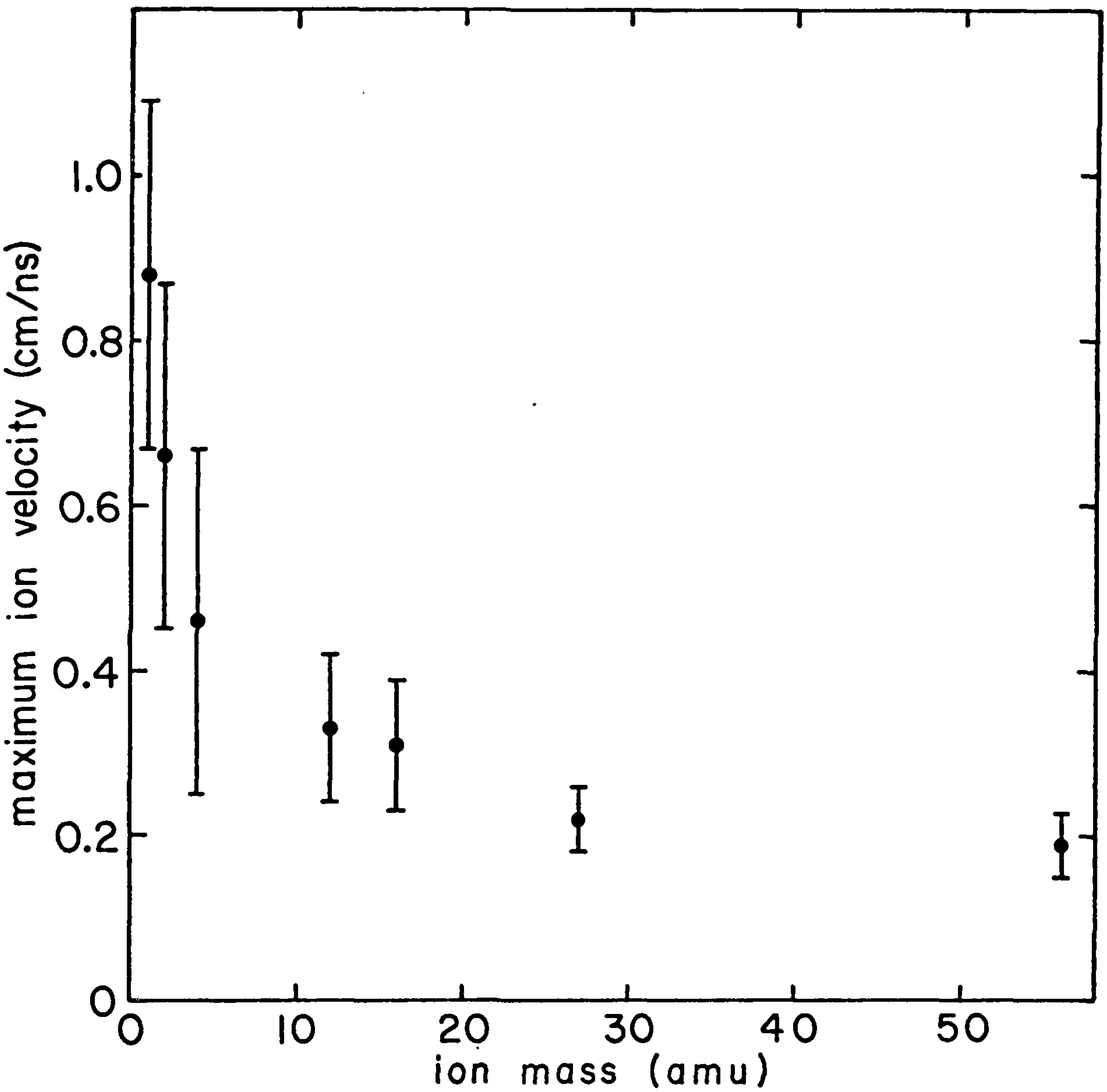

Figure 7.
Plot of maximum ion velocity versus ion mass as summarized from the data in Table 2. Note the data for all ions having the same mass, regardless of charge state, are combined (e.g. C^{3+}, C^{2+}, and C^{+}). The error bars represent the standard deviation in maximum ion velocity over several shots.

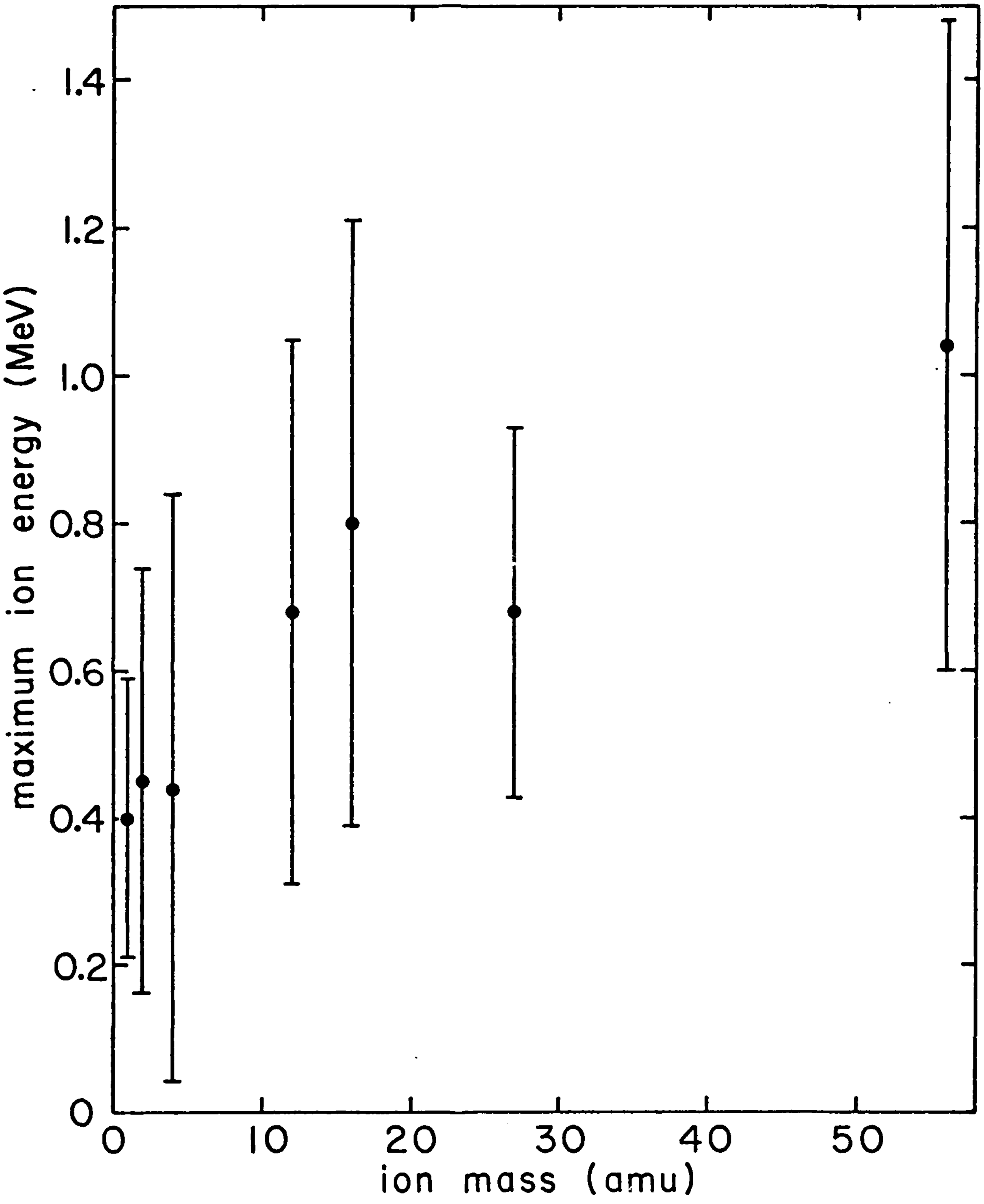

Figure 8.
Plot of maximum ion energy versus ion mass as calculated from the velocity data of Table 2. Note the data for all ions having the same mass, regardless of charge state, are combined (e.g. C^{3+}, C^{2+}, and C^{+}). The error bars represent the standard deviation in maximum ion energy over several shots.

dependent on ion mass (the maximum energies lie in the range from 0.5 to 1.5 MeV); and (4) carbon impurity ions are present in almost every shot, while protons are also a dominant impurity ion. One additional interesting observation is that no ions are observed whose mass is greater than the mass of the cathode/anode material. Carbon cathodes and anodes were used except for shots 111910, 112004, and 112303; for which both electrodes are stainless steel. Only in these three shots are the heavier ions of oxygen, aluminum, and iron observed.

Table 2 Thomson Parabola Maximum Velocity Results

Ion Source	Shot #	Maximum velocities of identified ions (cm/ns)										
		H^+	H_2^+	He^+	C^{3+}	C^{2+}	C^+	O^{2+}	O^+	Al^+	Fe^{2+}	Fe^+
H	100202	1.05				0.29	0.29					
H	100403				0.40	0.40	0.36					
H	100404						0.17					
H	102104	1.21	1.02									
H	110309	0.72										
He	100407			0.70	0.70	0.33	0.32					
He	100502			0.35	0.35	0.28	0.29					
He	100504			0.32	0.32	0.32	0.31					
Al	111806	0.77					0.25					
Al	111901	0.78	0.51		0.31	0.31	0.31					
Al	111904				0.27	0.27	0.27					
Al	111907	1.00					0.21					
Al	111910	1.26			0.57	0.58	0.54		0.33			
Al	112004	1.10	0.60			0.49	0.35	0.43	0.24	0.25	0.25	0.17
Al	112303	0.90	0.62			0.36	0.36	0.27	0.27	0.19	0.19	0.16
W	111601	0.66				0.21	0.35					
W	111701	0.68			0.33	0.33	0.34					
W	111704	0.76	0.53		0.30	0.30	0.30					
W	111706	0.71			0.30	0.30	0.30					
W	111801	0.67				0.30	0.30					

d. Comparison of Results. These ion results show it is possible to obtain ion species from a selected ion source, but ion impurities may play a dominant role in the ion acceleration process. Although ion velocities as determined by ion time of flight and Thomson parabola analysis reveal somewhat different results, they exhibit the same trend where the lighter ions achieve higher velocities.

3. Electron Beam Behavior During Ion Acceleration. Time resolved and time integrated measurements of beam propagation were accomplished. The beam front velocity was measured using two axially separated x-ray PIN diode detectors. The time integrated Bremsstrahlung x-ray exposure was mapped using thermoluminescent dosimeters (TLD's).

a. Beam Front Velocity Measurements. The x-ray PIN diodes were positioned (see Fig. 1) to give a time integrated x-ray pulse, where the x-rays are the result of the electron beam-drift tube wall collisions. The leading edge of this pulse signifies the approach of the beam front. For the time of flight measurement two of the PIN detectors were placed 30 cm apart in the drift tube region. Representative traces are shown in Fig. 9, and the numerical results are listed in Table 3. For hydrogen and helium ion sources the beam front velocity ranges from 1.2 cm/ns (peak to peak) to 2.0 cm/ns (leading edge). Using the tungsten plasma ion source, the characteristic beam front velocity varies from 1.3 cm/ns (peak to peak) to 2.9 cm/ns (leading edge). The downstream signal exhibits a "precursor" to the leading edge feature of the pulse. This precursor may be due to the portion of beam current which is below the initial space charge limiting current. Note for test shots where no ion source is provided the PIN detector near the anode shows a very large signal, while the downstream detector signal is very small. This indicates that when no ion source is present the beam remains

BEAM FRONT TIME OF FLIGHT

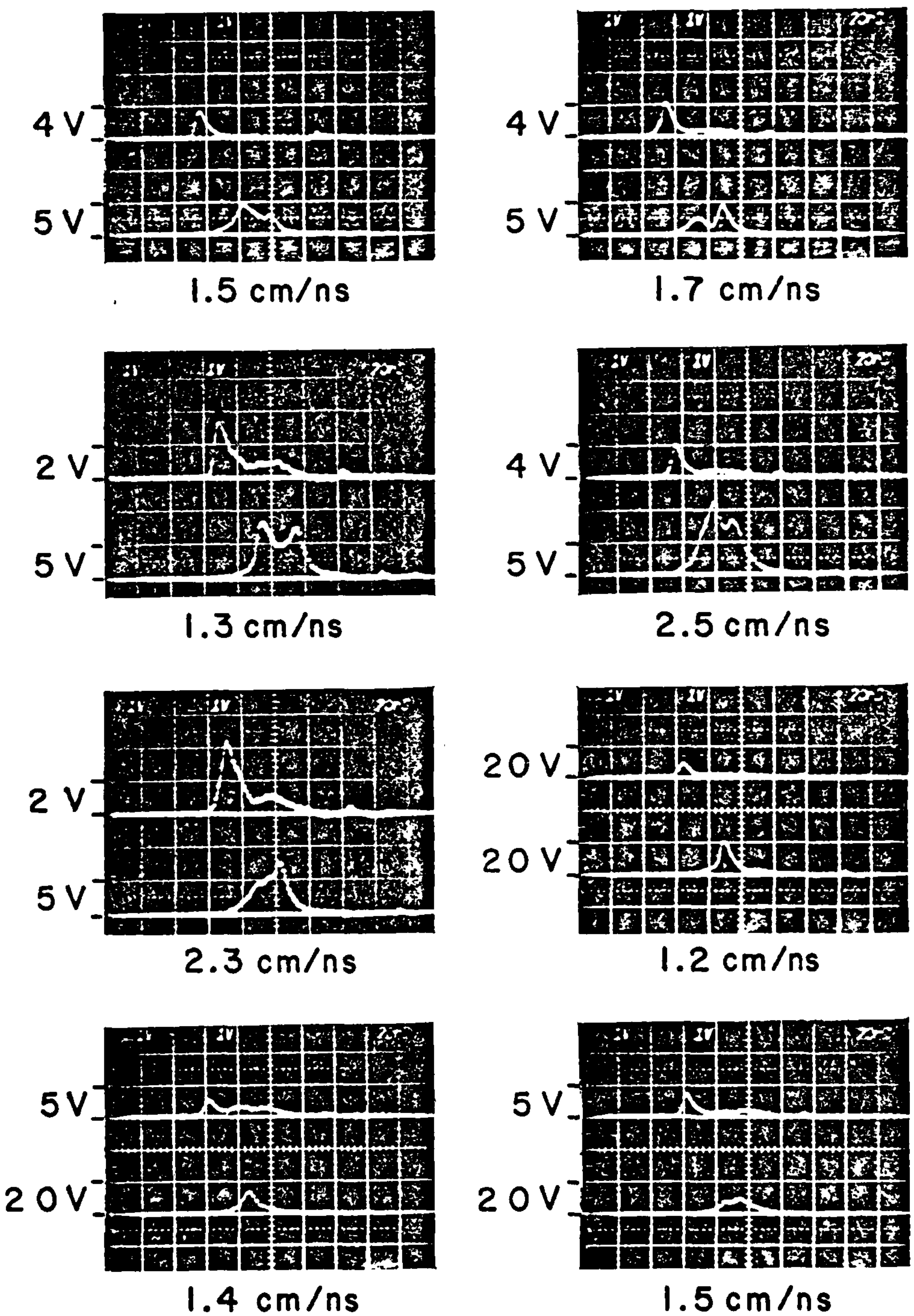

Figure 9.
Results for the beam front time of flight measurement using a H gas ion source. The upper/lower trace is the signal from the PIN diode located at Z = 4 cm/34 cm. The beam front velocity averaged over many shots is 2.0 cm/ns (4 inch I.D. drift tube) where the pulse leading edge is used for measurements.

"stopped" near the drift tube entrance while relatively little of the beam propagates.

Note the beam front velocity and ion time of flight velocity results compare favorably. Also recall the Thomson parabola data showed the lightest mass ions (protons) achieved the greatest velocities. From these two observations it appears that protons are trapped in the moving potential well of the beam front, while the larger mass ions are lost out of it.

Table 3 Pin Diode Beam Front Velocity Results

	Beam Front Velocity as Measured Using		
Ion Source	Beginning (cm/ns)	Leading Edge (cm/ns)	Peak (cm/ns)
H	3.0 ± 1.4	2.0 ± 0.7	1.2 ± 0.2
He	2.5 ± 1.2	2.1 ± 0.8	1.1 ± 0.2
W	3.0	2.9 ± 1.4	1.3 ± 0.3

b. Measurements of Axial and Azimuthal Profiles of Electrons Striking Guide Tube Wall. Thermoluminescent dosimeters are used to measure time integrated Bremsstrahlung x-ray exposure. A mapping of this exposure shows the characteristics of beam propagation in the drift tube. TLD's were positioned around the drift tube wall and at the drift tube endplate as shown in Fig. 10. Three dimensional x-ray exposures are plotted in Figs. 11 through 15 for both gas and plasma ion source shots, and also where no ion source was provided. Some observations from the drift tube wall mappings are: (1) beam transport characteristics for a shot are nonuniform and from shot-to-shot are erratic; (2) relatively little if any of the beam propagates for the "no ion source" case; (3) for some shots it appears the beam is channeled into a localized region on the drift tube wall. Observations for the endplate mappings, which give a time integrated cross section beam profile, are: (1) beam profile appears relatively constant in some shots, and peaked

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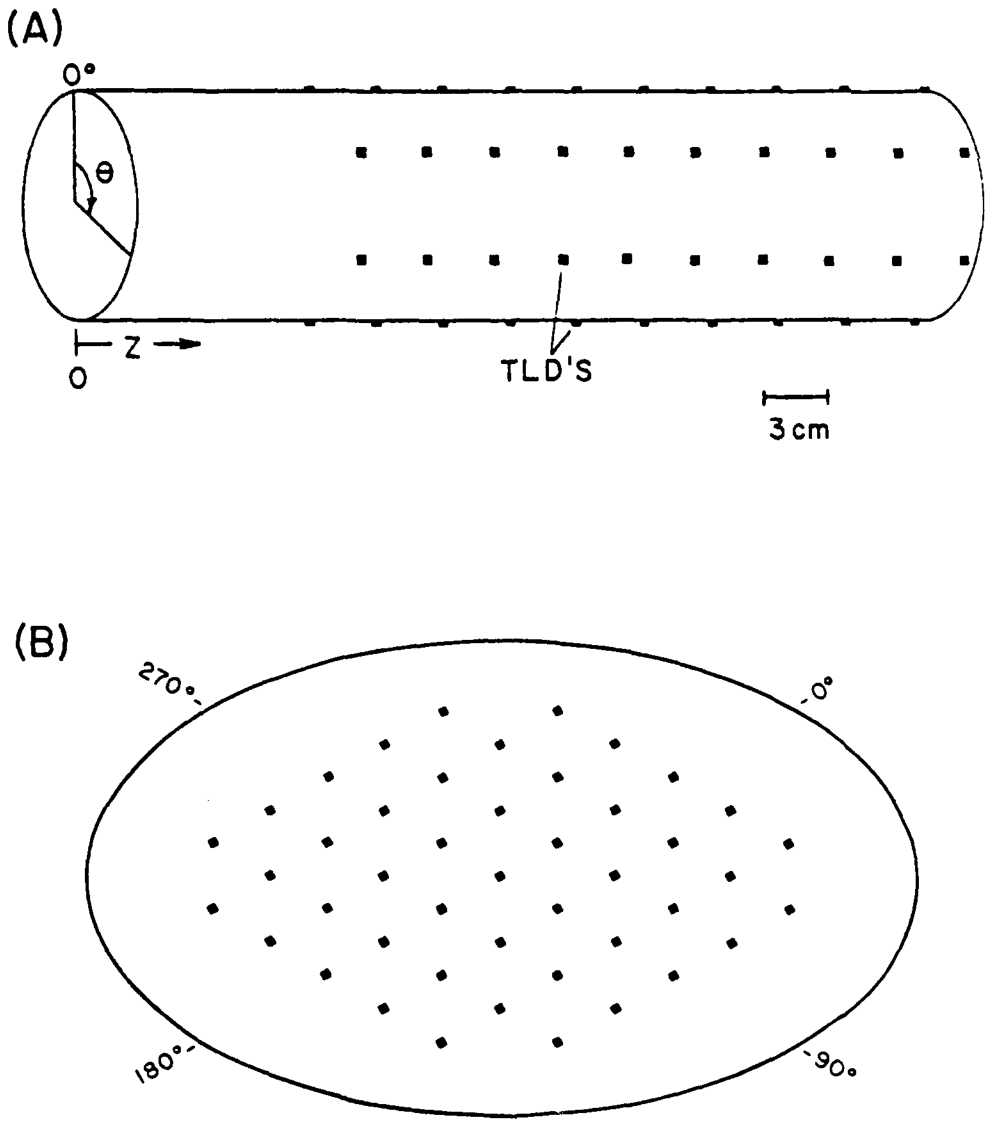

Figure 10.
Diagrams showing the location of TLD's used in measuring x-ray exposure and the coordinate system used in plotting the resultant data. Picture (A) shows the 'drift tube wall' configuration where the anode plane is located at z=0. Picture (B) shows an oblique view of the 'endplate' configuration where the outer boundary corresponds to the 4 inch I.D. drift tube and the TLD's are spaced at 1 cm intervals.

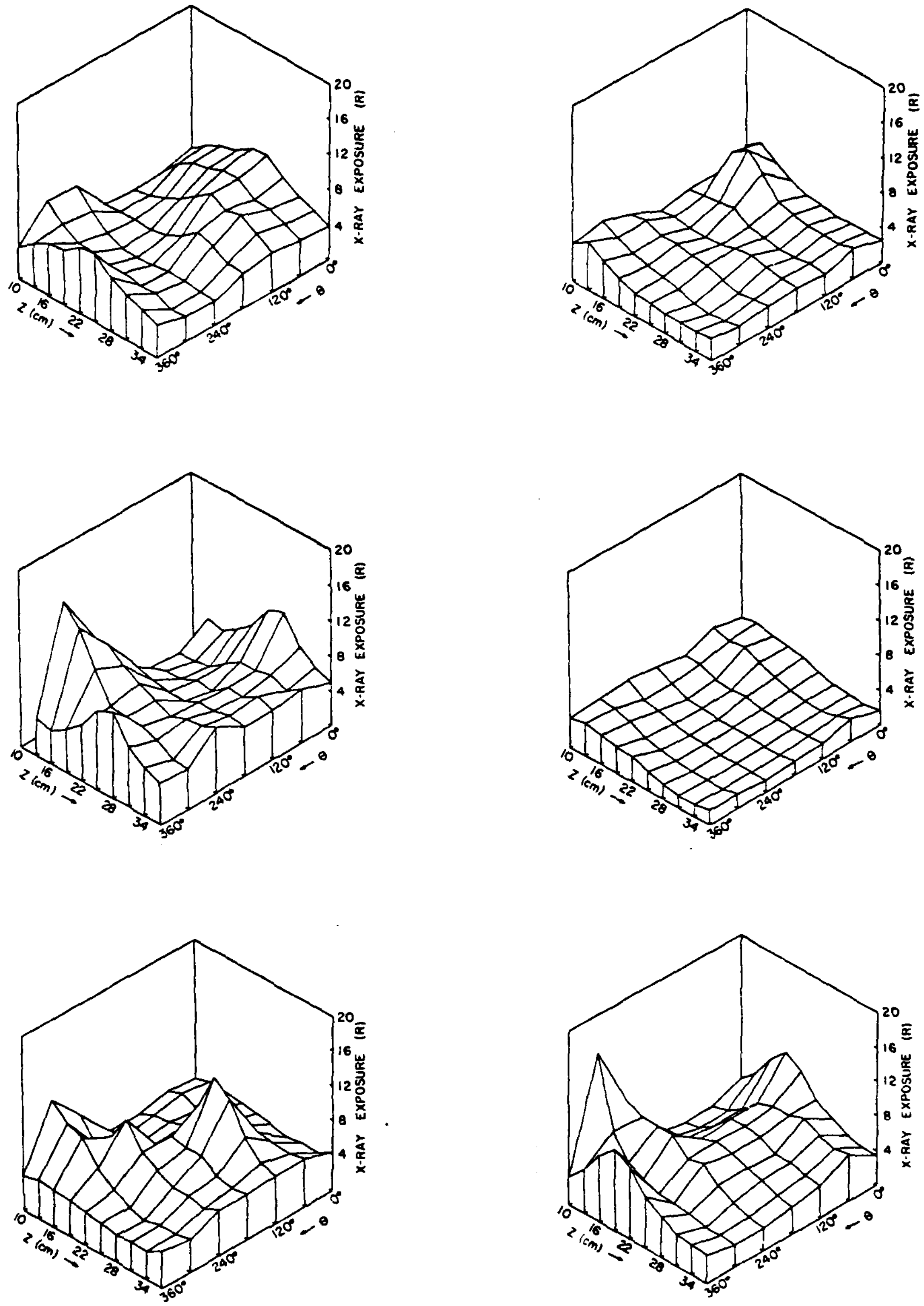

Figure 11.
X-ray exposure profiles for a H gas ion source using TLD's in the drift tube wall configuration.

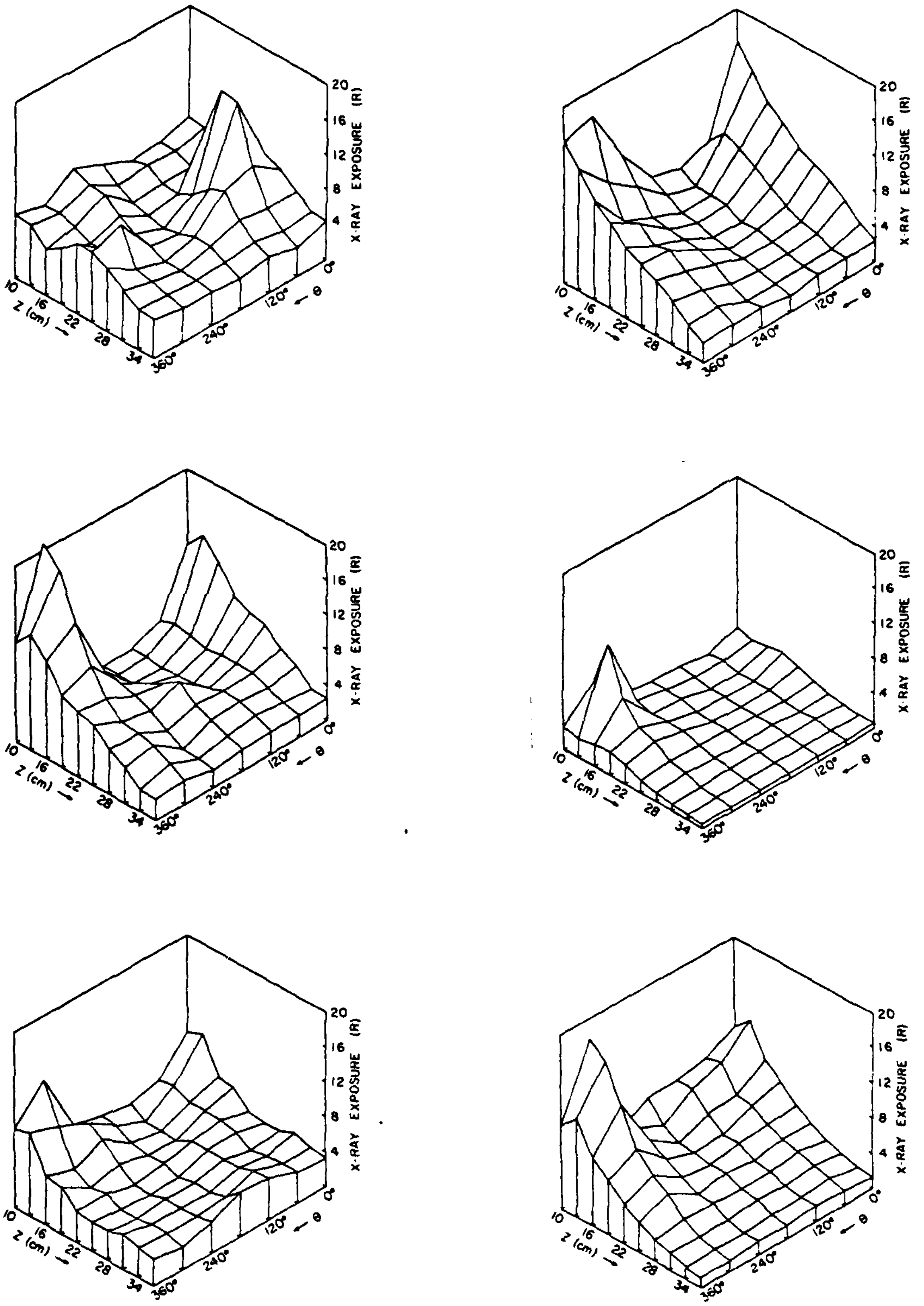

Figure 12.
X-ray exposure profiles for the He and N gas ion sources using TLD's in the drift tube wall configuration.

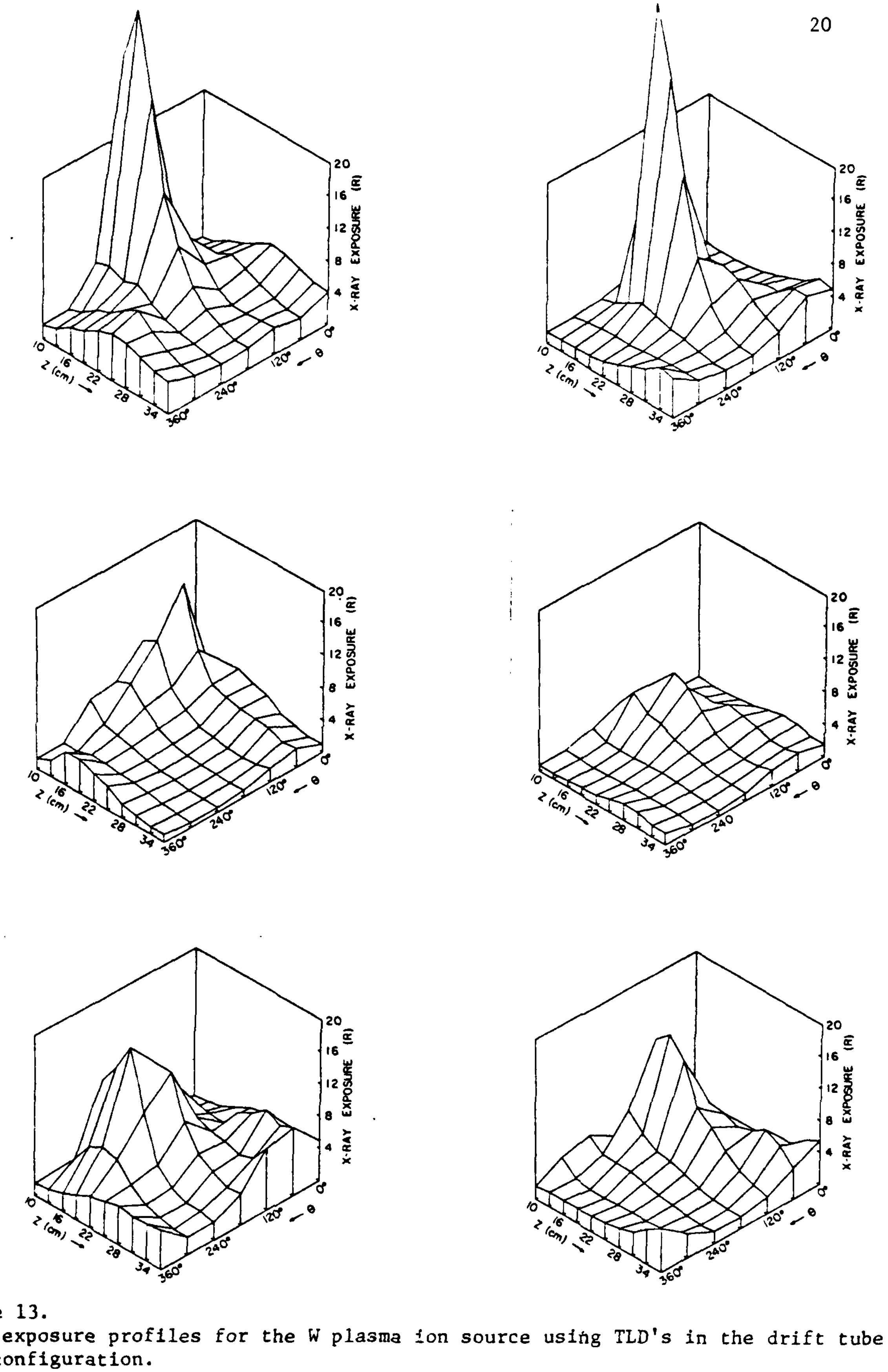

Figure 13.
X-ray exposure profiles for the W plasma ion source using TLD's in the drift tube wall configuration.

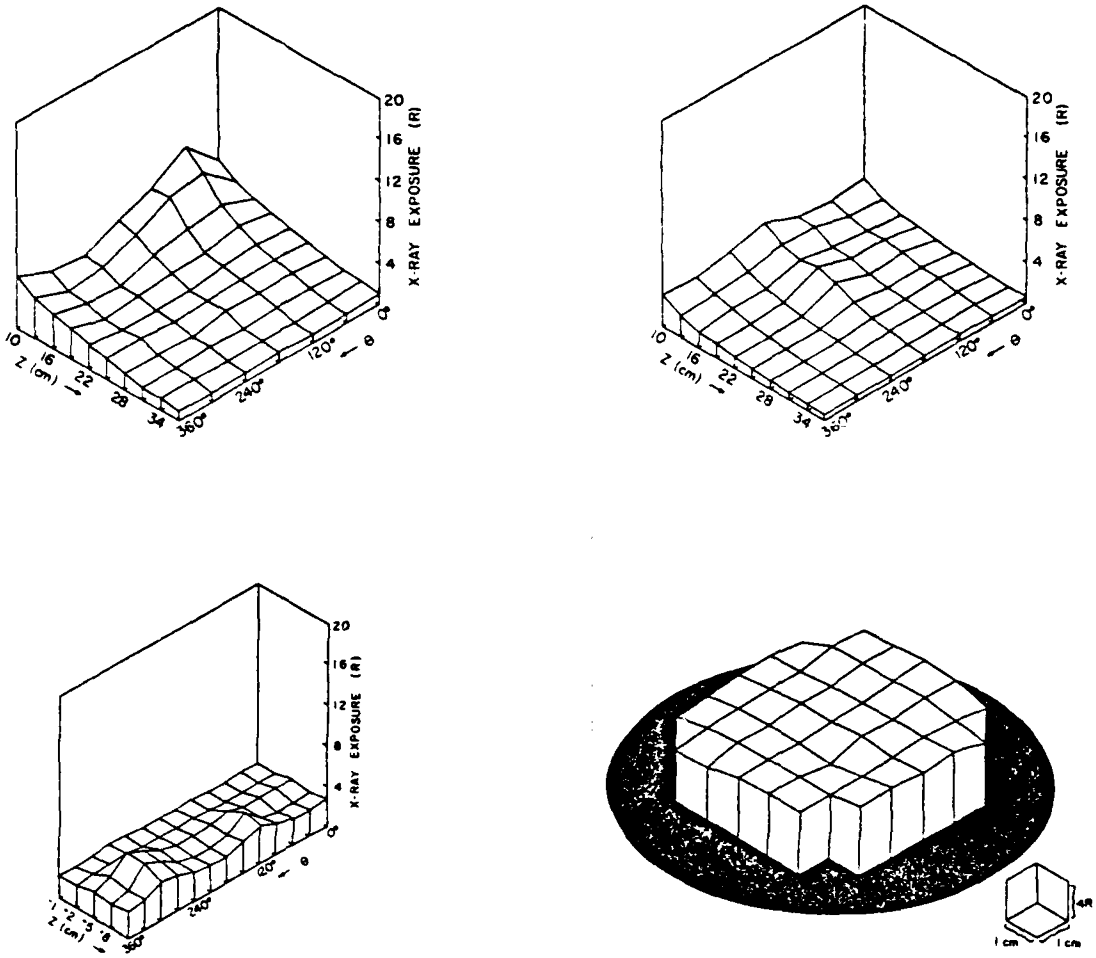

Figure 14.
X-ray exposure profiles using no ion source for TLD's in both drift tube wall and endplate configurations.

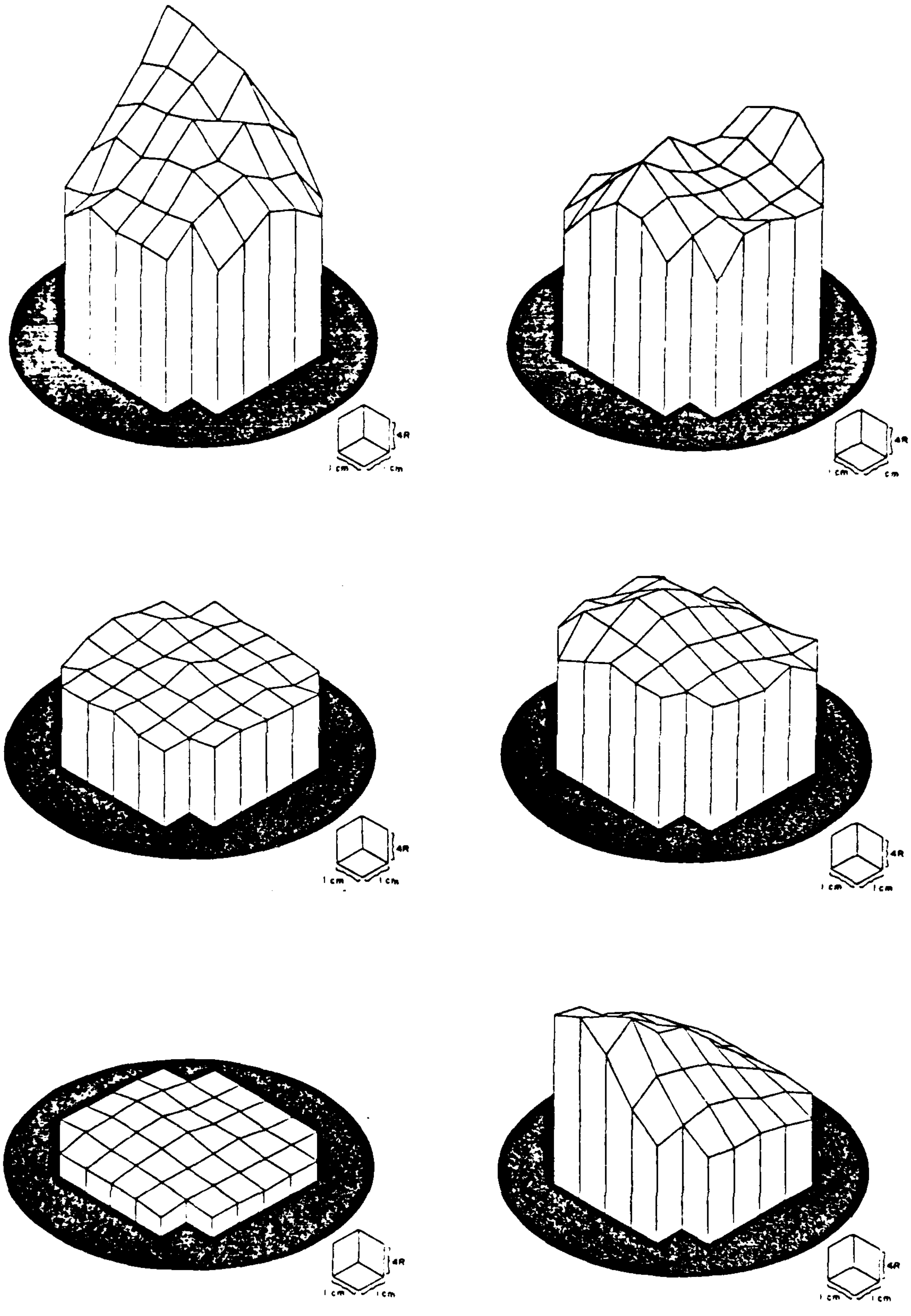

Figure 15.
X-ray exposure profiles for the H gas ion source using TLD's arranged in the endplate configuration.

in others; and (2) quantity of propagated beam shows shot-to-shot variation. Note since this is a time integrated measurement the constant cross section profiles could be the result of (1) a constant profile during the entire beam pulse or (2) a beam that whips around in time, which results in a time averaged profile that appears constant. The shot-to-shot variation in the x-ray mappings is consistent with the erratic behavior encountered in the accelerated ion measurements.

C. Relativistic Electron Beam Quality Studies and Experiments

Electron beam quality investigations have been carried out in close collaboration with Drs. Robert K. Parker and V. L. Granatstein at the Naval Research Laboratory using the VEBA machine. All of this work will be fully reported in the 1982 Ph.D. dissertation by Robert H. Jackson which is about 60 percent written, copies of which will be forwarded to AFOSR in the fall where they become available. Several publications have appeared which describe the important findings and are attached to this final report. Abstracts of some of these publications follow.

1. "Design and Operation of a Collective Millimeter-Wave Free-Electron Laser" by R. H. Jackson, S. H. Gold, R. K. Parker, H. P. Freund, P. C. Efthimion, V. L. Granatstein, M. Herndon, A. K. Kinkead, J. E. Kosakowski, and T. J. T. Kwan. To appear in Journal of Quantum Electronics, February 1983.

A new free-electron laser experiment has been designed at NRL to operate at millimeter wavelengths using a collective beam-wave interaction. Critical features of the experiment include an apertured diode which provides a low emittance electron beam, a wiggler magnet with adiabatic entrance and exit, and an operational domain centered around the wiggler-guide field gyroresonance. With the experiment configured as a superradiant amplifier, the effects of the gyroresonance on beam dynamics and the beam-wave

interaction have been studied. Measurements indicate a peak power production of 35 MW at 4 mm with an electronic efficiency of 2.5%. Aspects of the experimental design are discussed, and the results of a parametric study of the power dependence on the fields are presented. Detailed calculations (both analytic and computational) have been performed to analyze the linear and nonlinear effects in the experiment. The results of these calculations are shown to be in good agreement with laboratory measurements.

2. "Helical Magnetic Field Effects on Beam Quality," R. H. Jackson, R. K. Parker, S. H. Gold, and P. E. Ferguson. 1982 IEEE International Conference on Plasma Science, Ottawa, Canada, May 17-19, 1982.

Helical magnetic fields have proven useful in free-electron laser[1] (FEL) and gyrotron[2] experiments because substantial transverse velocity can be imparted to a beam initially propagating along the axis. Theoretical analyses[3] of beam motion in combined axial and helical magnetic fields have either linearized the equations of motion or used the ideal helical field approximation:

$$B_{HELIX}=B_H[E_X COS(K_O Z)+E_Y SIN(K_O Z)]$$

where B_H = constant, $K_O = 2\pi/L$, and L = helix period. The ideal field neglects the beam entrance into the helical field and the spatial variation of the field, both of which effect the quality of the electron beam. The complexity of the actual helical field[4] makes theoretical analysis difficult, and standard 2-D and single particle computer codes are inadequate. Therefore a new code (Track-3) has been developed to examine beam quality in experimental

helix configurations. Track-3 has been used to investigate beam motion in the tapered bifilar helix of the NRL MM-wave FEL experiment[1]. The effects of the tapered-field entrance and the 1st order helix field on beam quality were studied as a function of proximity to gyroresonance[1,3]. The entrance was found to produce coherent velocity oscillations about the ideal orbit values. The 1st order field gradients cause a thermal spread in electron velocities. Both effects were found to increase faster than exponential as the gyroresonance was approached. The investigation is being extended to include beam self-fields and higher order helix fields. Also the suitability of bifilar helix fields as transverse velocity drivers for gyrotron devices is being investigated.

[1] Parker, R. K., et al., Phys. Rev. Lett. 48, 238 (1982). Gold, S. H. et al., Companion paper at this conference.

[2] Ferguson, P. E., and Symons, R. S., IEDM Tech. Digest P198, Wash., D.C., December 1981.

[3] Freund, H. P. et al., Phys. Rev. A 24, 1965 (1981), and references therein.

[4] Poritsky, H., J. Appl. Phys. 30, 1828 (1959).

3. "Axial Magnetic-Field Effects in a Collective-Interaction Free-Electron Laser at Millimeter Wavelengths," R. K. Parker, R. H. Jackson, S. H. Gold, H. P. Freund, V. L. Granatstein, P. C. Efthimion, M. Herndon and A. K. Kinkead. Physical Review Letters 48, 238 (1982).

The collective free-electron laser interaction has been studied at millimeter wavelengths using a newly designed experimental apparatus which features an electron beam of low emittance. Measurements in a superradiant amplifier configuration indicate

the production of 35 MW at ~ 4 mm with an efficiency of 2.5%. The parametric dependences of power thresholds and wavelength on pump and guide magnetic fields are shown to be in agreement with theory.

III. LIST OF THESES, PAPERS PRESENTED AND PUBLICATIONS RELATED TO AFOSR GRANT 80-0051

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9-8